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The Measurement of the Effects of Helmet Form on Sound Source Detection and Localization Using a Portable Four-Loudspeaker Test Array

by Angelique A. Scharine and Tomasz R. Letowski

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14. ABSTRACT

The objective of this research was to evaluate the effectiveness of a portable, four-loudspeaker array for assessments of helmet effects on wearer's detection and localization of sound sources. Military and civilian helmets affect the wearer's ability to detect and localize sound sources. There is industry need to evaluate auditory effects in helmet development and modification processes, but ongoing, well-controlled laboratory studies are prohibitively time-consuming and costly. A portable four-loudspeaker test array was used to compare the auditory effects of two prototype and two fielded helmets to a bare-head condition. Detection thresholds were measured for one-third-octave noise bands (125–8000 Hz). Localization performance was assessed for low-pass (<500 Hz) speech sounds and high-pass (>2 kHz) breaking glass sounds in the presence of two background noises. Detectability of sound sources varied both with the helmet type and the sound source type/location. Average sound attenuation across all test conditions was less than ±1.5 dB for each helmet tested, but varied with frequency, reaching −7.0 dB for some helmets. Effects of helmet on sound source localization were large, significant, and varied with type of helmet.

15. SUBJECT TERMS

insertion loss, sound source localization, helmet design, spatial acoustics, sound attenuation

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Preface

Portions of this work were presented in “The Effects of Helmet Shape on Directional Attenuation of Sound” at the 16th International Congress on Sound and Vibration, Krakow, Poland, July 2009, and as “The Impact of Helmet Design on Sound Detection and Localization,” a poster presented at the 148th Meeting of the Acoustical Society of America, San Diego, CA, April 2005.

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1. Introduction

Military helmets are designed to provide ballistic protection of the head against direct and indirect impacts. The effectiveness of ballistic protection increases with increasing the area of head coverage, so in many cases the ears and the surrounding area are partially or completely covered by the helmet. Helmets also differ in their shape due to the addition of ridges and visors intended to allow incorporation of communications headsets or reduce glare from the sun. Two helmets may provide similar head coverage and yet differ greatly in the shape.

Coverage of the ear and changes to the profile of the listener's head resulting from the presence of a helmet change the spectral envelope of the sound wave that arrives at the listener's ear. Sound diffraction and scattering caused by the exterior of the helmet as well as sound reflection from the interior of the helmet will modify the level, temporal pattern, and spectrum of the arriving sounds, affecting the Soldier's ability to detect and identify sound sources, and possibly distort the spatial perception of the direction of the incoming sound (Scharine et al., 2009). These effects are exacerbated by reverberation and the use of hearing protection (Scharine et al., 2009; Abel et al., 2009).

The need for accurate auditory perception by Soldiers has been recognized by the research community and Soldier system developers for quite some time. The U.S. and British helmet used during World War II, known as the M-1 helmet, consisted of two parts: an external "steel pot" shell and an internal hard-hat type liner that contained the suspension system. The shell was constructed from a single circular piece of steel and was flared at the bottom, providing a crimped metal band forming a rim. The resulting shape was heavily criticized for its interference with hearing. It produced standing-waves, which resulted from multiple sound reflections waves from internal surfaces of the helmet, and affected perception of high-frequency sounds. In their historical memorandum, Houff and Delaney (1973) identified two basic acoustic requirements regarding military helmets: they should (1) attenuate damaging noise yet allow perception of noninjurious sounds and (2) be shaped in a way that does not undermine speech perception or sound source localization. They also stressed the need for an evaluation of the benefits gained from extended ballistic protection vs. the loss of situation awareness.

The two best-known studies of the effects of military helmets on auditory perception are those by Randall and Holland (1972) and Forshaw et al. (1987). The authors of both studies reported small but detrimental effects on sound detectability produced because the helmets occluded, or partially occluded, the ear canal. Randall and Holland measured sound attenuation caused by the M-1 helmet (figure 1, left) and a prototype helmet known as the Hayes-Stewart helmet (figure 1, center). They studied the helmet-induced changes in hearing threshold for seven pure tones (125, 250, 500, 1000, 2000, 4000, and 8000 Hz) presented from five directions (0, 45, 90, 135, and 180°) and found small sound-level effects on the order of a few decibels. In the case of the M-1 helmet, the average amount of directional attenuation calculated across all frequency values varied from 0 dB at 0° to 3.5 dB at 90° and 2.2 dB at 180°. The Hayes-Stewart helmet, which has cut-outs around the ears to facilitate auditory awareness of the environment, raised hearing thresholds by only about 1.2 dB, and this effect was independent of sound source direction. The sound attenuation caused by both helmets was, when averaged across angles, negligible for frequency signals below 1000 Hz. For frequencies above 1000 Hz, attenuation values reached 2 dB for the Hayes-Stewart helmet and 5 dB for the M-1 helmet.

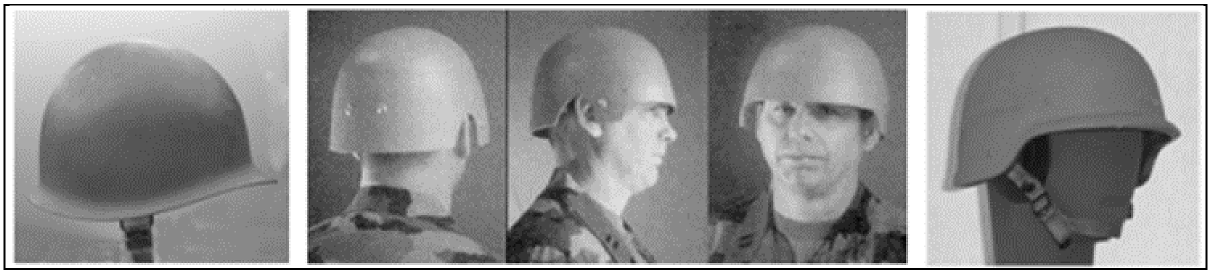

Figure 1. U.S. Army helmets. From left to right, the M-1 helmet, the Hayes-Stewart prototype shown from three angles, and the PASGT helmet.

The Personnel Armor System for Ground Troops (PASGT) helmet (figure 1, right), introduced in 1971 to replace the M-1 helmet (Houff and Delaney, 1973), differs most significantly from the M-1 helmet by including lower sides, providing extended head and ear coverage, and a front edge that ends a little bit higher above the eyes. Forshaw et al. (1987) evaluated a Canadian version of the PASGT helmet using audio recordings made with a bare Knowles Electronic Manikin for Acoustic Research (KEMAR) and a KEMAR manikin outfitted with the helmet. The test signals were created by filtering white noise into one-third-octave bands centered at frequencies ranging from 125 to 16,000 Hz and presented from 0º, 90º, and 180° azimuth. The differences in the measured sound level between the bare head and the helmet conditions were similar to the data reported by Randall and Holland; however, the absolute values were higher. The observed shifts in sound level were less than 3 dB at low frequencies but increased to 9 dB in the high-frequency range. The shifts in the detectability levels for sounds coming from the front, side, and back were in the –4/+2 dB, –2/+9 dB, and –3/+6 dB range, respectively. Forshaw et al. also observed a significant helmet-induced sound amplification in the 1-kHz range regardless of the direction of incoming sound.

The insertion losses reported in both studies were fairly minimal and certainly not sufficient to protect the helmet wearer against harmful levels of noise or significantly affect sound detectability. However, because these effects are frequency-dependent, they can significantly alter a sound’s spectral envelope, affecting the cues used to localize the directions of incoming sounds. Evaluations documenting these differential effects in helmet design have been conducted in support of protective gear development, but much of this research is not published. The data that have been published suggest that helmet presence increases localization uncertainty as well as the probability of front-back localization errors (Scharine et al., 2007).

This report details the effects of four helmets on listener hearing thresholds and localization ability. Two of the helmets are the standard military Kevlar* helmets fielded by the U.S. Army. The other two helmets are prototype helmets under development by the U.S. Army. This report replicates other studies of helmet effects on localization for the purpose of testing whether a small portable four-loudspeaker array would be sufficient for measurement of helmet effects on localization. This array was built to allow those designing helmets to conduct simple comparisons and evaluations without having access to expensive, well-controlled test facilities. We will present analyses of the data to show that although the acoustics of the test facility were not ideal, the data is sufficient to allow comparison of the helmets' impact on hearing.

2. Experiment 1: Helmet Effects on Sound Source Detection

In experiment 1, the listener's detection threshold for 200-ms long sounds was measured with one-third-octave bands of white noise centered at 250, 500, 1000, 2000, 4000, 6000, and 8000 Hz. The thresholds were measured for five listening conditions (four helmets and the bare head). The goal of the study was to demonstrate that while helmet attenuation is minimal, it is direction- and frequency-dependent and can be quantified using a small loudspeaker array.

2.1 Method

Participants. Threshold measurements were made for four participants (one male, three female) ages 21 through 30. All participants had normal hearing defined as air conduction thresholds of less than or equal to a 15-dB hearing level at octave frequencies from 250 through 8000 Hz.

Helmets. Four helmets (figure 2) were selected for inclusion in the study; two current U.S. Army helmets (PASGT and advanced combat helmet [ACH]) and two prototype helmets (R4R and R4). The PASGT helmet is the legacy helmet of the U.S. Army that is gradually being removed from service; its protective shell covers approximately three-quarters of the ear canal. The area around the ear and in the front of the helmet is flared; the front area is a visor to reduce sun glare and protect against rain. The suspension system is a webbed net attached to a ring that suspends the helmet approximately 0.5 in above the surface of the head. It is attached to the head using a two-point chin strap.

*Kevlar is a registered trademark of Dupont.

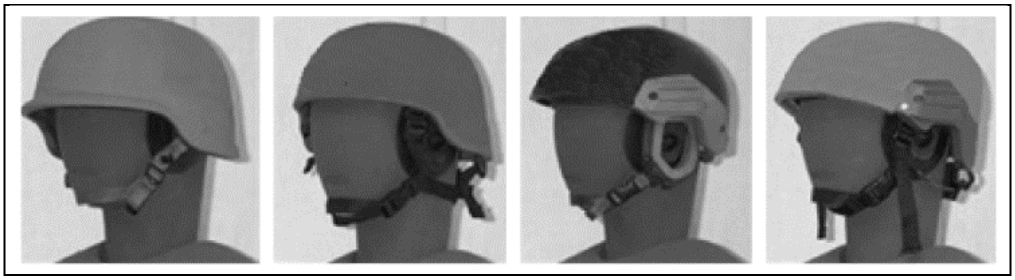

Figure 2. The four helmets evaluated in the study. From left to right: PASGT, ACH, R4R, and R4. Note that although the R4R and R4 helmets pictured are different colors, the only physical difference is the mounting ring around the ears of the R4R.

The ACH is the current infantry helmet of the U.S. Army. The helmet has approximately 11% less coverage of the ears than PASGT and has no visor. The suspension system of the helmet consists of a number of adjustable foam pads providing required stand-off distance from the head. The ACH is attached to the head by a chin strap attached at four points, allowing adjustment at the back of the head and at the chin.

The R4R helmet is one of the prototypes being developed for the U.S. Army. The version tested had a foam inner shell, a fit ring around the head, and a chin strap attached at two points. The characteristic features of the R4R are two open mounting rings that extend from the helmet and encircle the ears. The purpose of these rings is to hold optional earmuff cups that could be inserted into these rings for hearing protection. The R4R configuration with the earmuffs was not tested.

The R4 helmet, another prototype, is identical to the R4R except that the mounting rings had been removed, leaving the entire ear region uncovered and providing the least head coverage of all four helmets.

Test facility and loudspeaker array. The listener was seated in the center of an array of four loudspeakers located at 0°, 90°, 180°, and 270° angle and 1 m from the listener (figure 3). The listener's chair was placed on an adjustable platform to ensure that both of the listener's ears were at the height of the loudspeakers. Each listener was seated in one of two orientations for half of the measurements and then turned 45° to collect thresholds for sounds presented from eight angles (0°, 45°, 90°, 135°, 180° 215°, 270°, and 315°) relative to the listener.

In experiment 1, sound source detection was measured with a 40-dB sound pressure level (SPL) "ambient" background noise-masker shaped to mimic the heating, ventilating, and air conditioning system in the experimental space (figure 4). Both "ambient" and "uniform" noises were used in experiment 2.

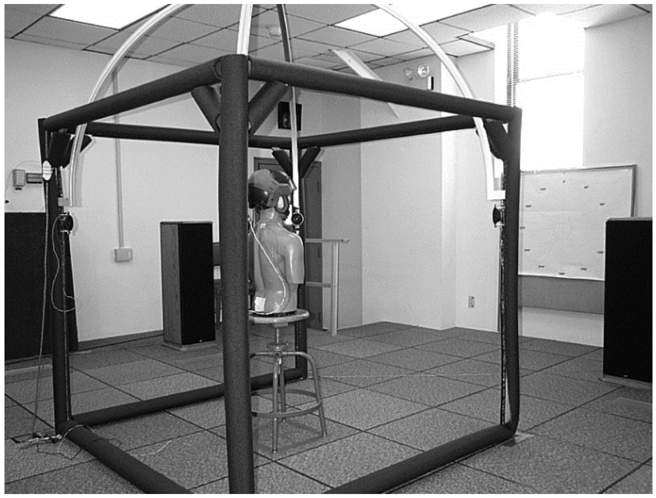

Figure 3. The loudspeaker array used for sound presentation.

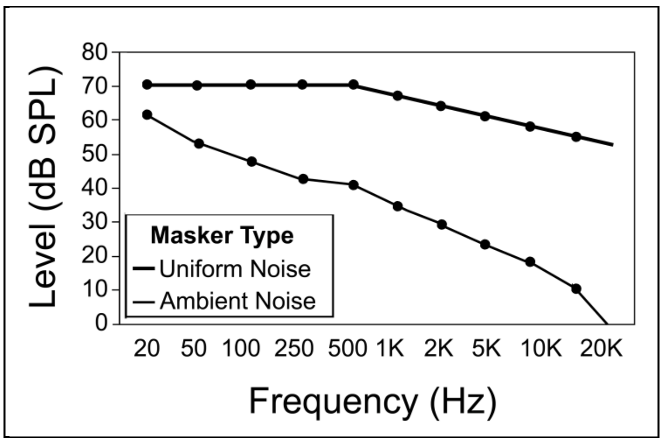

Figure 4. The spectral envelopes of the two masking noises used in the study.

Note that this testing setup was designed to assess whether a small portable array could be used to evaluated helmet designs. For this reason, all testing was conducted in a room that was not sound-treated (except for ceiling) or symmetrical; it was a large room ($V = 134\ m^3$) with a reverberation time of RT=0.45s at a frequency of 1000 Hz.

Procedure. Prior to data collection, a rough estimate of each listener's binaural hearing threshold (with a bare head) was obtained for each of the test frequencies using the method of adjustment. This value was subsequently used to choose a 12-dB range (seven signals at 2-dB increments) for use in the detection threshold measurements. For each of the test frequencies, the target sound was initially presented at a clearly audible level, then the method of constant stimuli was used to present sounds at levels centered at the listener's previously determined hearing threshold. Lights on a response box placed in front of the listener indicated the time interval during which a signal could be presented and when a response was required. The listener's task was to press a green button if a signal was heard or a red button if none was detected. Four directional thresholds were obtained for each of the signals in each of the two listener orientations (eight thresholds altogether). The sequential order of the signal frequencies (descending vs. ascending) and the order of presentations across the loudspeakers and signal levels were randomized. This procedure was repeated for each of the helmets and for the bare head. The order of head conditions was determined by a Williams* counterbalance design (Williams, 1949).

2.2 Results and Discussion

In order to calculate the threshold of signal detectability for each azimuth and frequency, the listener's responses were plotted as a function of signal level for each condition and listener. The data were fitted by a probit function, and the point of subjective equality (defined as 50% correct) was used as the threshold value. The sound attenuation created by each helmet was then calculated as the difference between a listener's threshold with the helmet on and with the bare head. Figure 5 shows the overall attenuation of each helmet averaged across all angles and frequencies. Two effects are noteworthy. First, the overall attenuation was quite small—less than ±1.5 dB. Second, when the data is averaged across frequencies and azimuths, the R4R actually amplified the sound by about 0.5 dB.

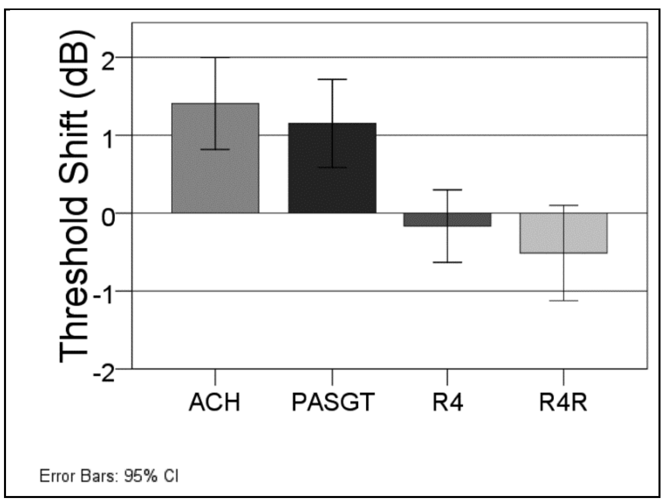

Figure 5. The threshold shift, relative to the bare head, measured for each individual helmet averaged across angles and frequencies.

The same threshold shifts, as a function of azimuthal sound source location, are shown in figure 6 (left- and right-side data are combined and shown on the left side because the effects were symmetrical about the centerline). For some helmets, the threshold shifts observed differed with source location. For example, the R4R helmet attenuated sounds coming from in front, but

*A Williams design is a specialized Latin square design that is also balanced for first-order carryover effects. That is, no one condition follows another condition more often than another condition.

amplified those arriving from other directions. The overall effect of the R4 helmet is relatively smaller but similar to the effect of the R4R helmet at angles other than zero. Both the ACH and the PASGT attenuated sounds arriving from the rear angles. In comparison to the two prototype helmets, they resulted in greater insertion loss across all angles.

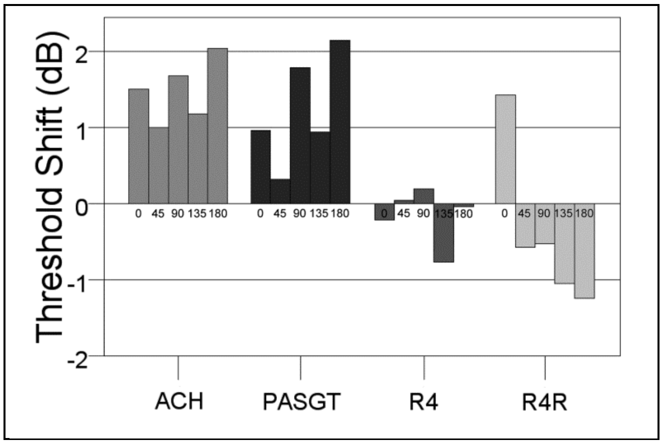

Figure 6. The threshold shift, relative to the bare head, measured for each individual helmet as a function of sound source azimuth location (averaged across the midline).

The effect of frequency on the direction and size of the threshold shift is shown in figure 7. An analysis of variance (ANOVA) was computed for attenuation with helmet type, azimuth (collapsed across the midline), and center frequency as factors and subjects as a covariate. The main effects of helmet and frequency were significant [$F(3, 699) = 6.09$, $p = 0.004$; $F(6, 699) = 9.62$, $p < 0.001$], as was their interaction [$F(18, 699) = 3.68$, $p < 0.001$]. There was no significant main effect of sound source azimuth; however, the interaction of helmet with azimuth was significant [$F(12, 699) = 2.59$, $p = 0.006$]. The amount of attenuation also varied significantly as a function of frequency and angle [$F(24, 699) = 3.09$, $p < 0.001$].

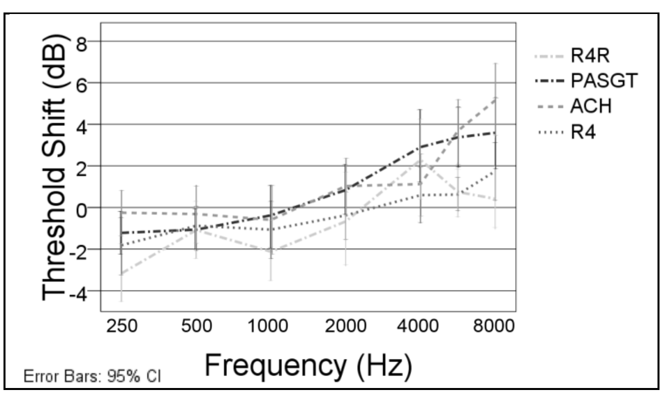

Figure 7. The threshold shift, relative to the bare head, measured for each helmet at each frequency.

Note that although these measures were obtained from a relatively small number of listeners, the data for the ACH and PASGT helmet align well with other attenuation data collected using rifle shots, clicks, and warble-tones (Scharine et al., 2009). The physical attenuating effects of the helmet are relatively stable and the helmet-induced attenuation measured for a listener is computed with respect to the hearing sensitivity of the same listener with unoccluded ears. The human auditory system uses the direction-dependent changes to the spectral content of sounds as a monaural localization cue (Moore, 2012). Thus, any changes to the spectral content due to helmet use may interfere with localization. The localization errors (both constant and random[*]) observed in this experiment were fairly large and equally distributed across all angles with some dominance of back vs. front errors. This was primarily due to the difficulty of the localization task under the given experimental conditions. The size of localization errors due to the presence of the helmet increased also with sound frequency. As shown in figure 7, for three of the helmets there was increased attenuation at higher frequencies, most likely due to the reflection and absorption of high-frequency energy. The ACH was the helmet with the softest suspension system and presumably the most absorbent one. This helmet also consistently showed the most attenuation at 8000 kHz regardless of the angle of the arriving sound. In contrast, the R4R showed an atypical pattern of attenuation with respect to frequency. Although there was an increase in attenuation at 4000 Hz, there was very little attenuation at 6000 and 8000 Hz at all angles except 0°. Further, there was about 2 to 3 dB of amplification observed at 1000 Hz for all angles except 90° and about 5 dB of amplification at 250 Hz for all angles except 0º and 180°. The added amplification at 1000 Hz is probably due to the rings on the helmet acting as an extension of the pinnae, reflecting sound back into the ear and amplifying sounds at some frequencies. Thus, due to this unusual spatio-spectral behavior of the R4R helmet, we would expect to find significant differences in localization data for the R4R as compared to the other helmets.

3. Experiment 2: Helmet Effects on Sound Source Localization

The purpose of experiment 2 was to assess changes in a Soldier’s auditory localization ability due to wearing each of the helmets. Because humans operate in environments with variable noise levels and a variety of sound events, two “real world” signals and two levels of background noise were used in the study. The experiment was conducted with the same small portable array and for the same listening conditions as used in experiment 1 in order to evaluate the feasibility of the loudspeaker array for evaluating changes in helmet form on the sound localization ability of the wearers.

[*]See the description of various localization errors in the discussion of results of experiment 2, page 16.

3.1 Method

Participants. Nine participants (four male, five female) ages 21 through 30 took part in the sound source localization study. All participants had normal hearing as defined in experiment 1. Additionally, we required that they have bilateral differences of less than 10 dB for all test frequencies.

Stimuli. The stimuli used for measuring helmet effects on localization accuracy were two short (300 ms) “real-world” sounds: a sample of speech, “uh,” processed through a low-pass filter with a 500-Hz cut-off and a breaking glass sound processed through a high-pass filter with a cut-off of 2000 Hz. These signals were wideband enough to have their spectra distinctly modified by potential filtering effects of helmets and were sufficiently frequency-specific to differentiate between low- and high-frequency helmet effects. All target signals were presented at 60-dB SPL (as measured at the listener location).

The same ambient noise masker used in experiment 1 was used for half of the localization trials. For the other half, a 67-dB SPL uniform masker noise was used. This was a broadband noise with constant spectrum levels for frequencies below 500 Hz decreasing in level at the rate of 10 dB per decade (3 dB per octave) above 500 Hz (as shown in figure 4). This spectral envelope was chosen to conform to Zwicker’s description of a uniformly masking noise (Zwicker and Fastl, 1999).

Test facility and loudspeaker array. The same facility, loudspeaker array, and listening conditions described in experiment 1 were used.

The results of previous localization studies have shown that the accuracy and precision of the listener’s responses depend on the number and distribution of potential source locations (listener’s alternatives; real or assumed) (Perrett and Noble, 1995). In order to minimize these effects, simulated “virtual” locations were created by varying the relative contributions of an adjacent pair of loudspeakers so that the overall level at the listener’s ear remained consistent, but the output of the loudspeakers were either equal or weighted toward one or other of the loudspeakers to create the impression of being halfway, or one-quarter of the way, between the two real loudspeakers. The data from these trials are not reported here.

Procedure. Sound localization performance was measured for each listener with a bare head and with each of the helmets in each of the two orientations and in both background noise conditions. A circular chart with azimuth values at 30° increments from 0° to 360° was placed in front of the listener. Listeners were seated in one of the two orientations (0° or 45°) and asked to report verbally the perceived location of each of the target signals. Their responses were recorded by the experimenter located in the corner of the room. A block of trials consisted of presenting each of the two target signals (low and high) four times from each of the four loudspeakers and five randomly chosen “virtual” locations for a total of nine locations. A block of trials was presented for each combination of background noise and head condition for a total of 10 blocks. The order of blocks was determined by a Williams counterbalance design (Williams, 1949). The order of the trials within a block was randomized.

3.2 Results and Discussion

Baseline localization ability: constant and random error. The bare-head ambient noise condition was used in this study as a reference condition representing baseline human localization ability. The data obtained in this condition were also used to assess potential directional effects of surrounding space on the listeners' ability to localize sound sources. Large asymmetrical signed (constant) errors observed in this condition would suggest problems with the nonstandard test space rather than the test variables of interest (see Letowski and Letowski, 2011). The aforementioned reference data for both low- and high-frequency signals are shown in table 1. These values were calculated in reference to the true position of the sound source with the convention that a negative value means that the estimate was more toward the front than the actual position and a positive value would mean that the estimate was more toward the rear of the actual position.

Table 1. Signed error values obtained for the bare head given as a function of signal frequency and azimuth.

Type of Signal	**Source Azimuth (°)**							
	0	45	90	135	180	225	270	315
Uncorrected Data								
Low	77	20	1	–52	–95	–59	1	20
High	65	25	7	–43	–83	–55	0	25
Errors >90° Removed								
Low	3	6	2	–31	–8	–25	1	2
High	2	15	8	–30	–9	–30	–4	9

The data shown in an upper panel of table 1 (uncorrected data) show larger errors near 0° and 180°. These suggest the presence of reversals or front-back confusions that are commonly found in localization data (Stevens and Newman, 1936). The relatively better performance for high-frequency signals is consistent with the fact that the spectral information that allows disambiguation of binaural cues lies primarily in the higher frequencies. For the analysis shown in the second half of table 1, we removed errors that were likely due to reversals (those greater than 90°). The remaining errors are most likely local error (Carlile et al., 1997). Local error differs little between the low- and high-frequency conditions. The large constant errors observed for 135º and 225º are consistent with other studies where listeners overestimated the laterality of the sound sources located in the rear hemisphere (for examples of this bias for broadband signals, see Oldfield and Parker, 1984). The small size and azimuthal symmetry of the remaining local errors suggest that despite the nonlaboratory acoustics of the room, no significant systematic errors were occurring due to the acoustic properties of surrounding space.

Any sensory system is subject to a certain amount of system noise that shows up in performance measures as random error dependent on both the stability of the observer's criteria and task difficulty. Random errors calculated as the standard deviations of the signed errors observed for the bare-head low-noise condition are listed in table 2.

Table 2. Random error values (degrees) obtained for the bare-head condition as a function of signal frequency and azimuth (ambient noise condition only).

Type of Signal	**Source Azimuth (°)**							
	0	45	90	135	180	225	270	315
Uncorrected Data								
Low	79	30	18	37	74	38	19	27
High	81	64	20	31	61	38	18	38
Errors >90° Removed								
Low	9	30	18	33	21	35	19	27
High	6	24	20	29	20	33	18	29

Random error values for the bare-head conditions are relatively large even when front-back errors are removed from the analysis. They are most likely due to task difficulty resulting from short test signals and small differences in listeners' head positions during the study. The data shown in table 2 also indicate a pattern of larger random errors for azimuth angles at which the data were collected during the rotated position of the listener (45°, 135°, 225°, and 315°). The listeners were required to respond by assigning a numerical value to a spatial location based on the circular reference chart that had labels in 10º steps. Inspection of the data shows a tendency for estimates to be multiples of 10, suggesting that in many instances participants may have responded with a rounded value, for example 140º rather than 135º, leading to a higher rate of random error on the diagonals. That pattern is observed throughout the analyses presented here but does not vary as a function of the helmet worn. It can be concluded that the data presented in tables 1 and 2 suggest that the data obtained from our portable loudspeaker array can be considered valid for comparison purposes, although the absolute size of errors would probably differ under other measurement conditions.

Helmet effects on sound source localization. Figure 8 shows the average magnitude of errors (computed as the unsigned difference between the perceived and actual azimuth) observed for each of the helmet conditions as a function of signal type. It is a partial sum of constant and random errors and can be considered an overall estimate of the difficulty of correctly estimating sound source location. In comparison with the root-mean-square error, which is the geometrical sum of constant error and random error, it de-emphasizes the role of random error in the overall error (Letowski and Letowski, 2011). This type of error was commonly reported in previous sound localization literature and was calculated here for comparison purposes.

The effect of sound source azimuth is similar to that reported in the literature for short sounds arriving from unknown directions (Oldfield and Parker, 1984; Butler, 1986). The differences between helmets seems to be driven primarily by differences in errors near 0° and 180°, as shown in figure 9 for each of the background noise conditions. These differences are exacerbated by the ambient noise in which testing occurred. The uniform masker masks high frequencies and the monaural cues used to distinguish the front and rear hemispheres. Similarly, low-frequency stimuli lack energy in the spectral regions needed to derive those cues.

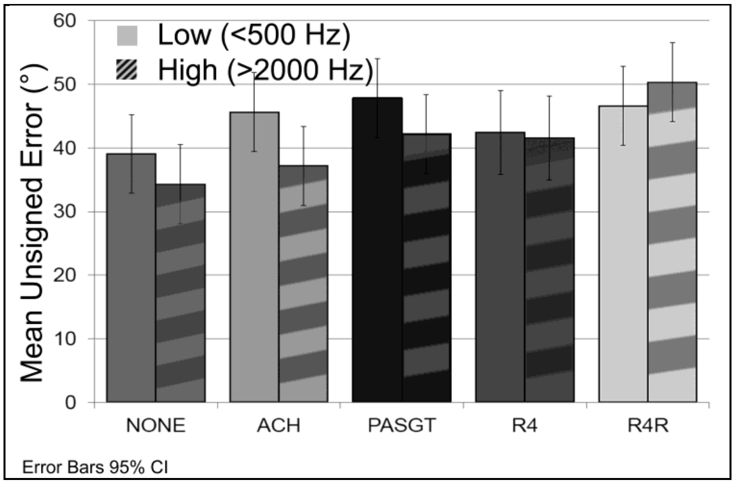

Figure 8. Mean unsigned localization error* as a function of helmet and signal type.

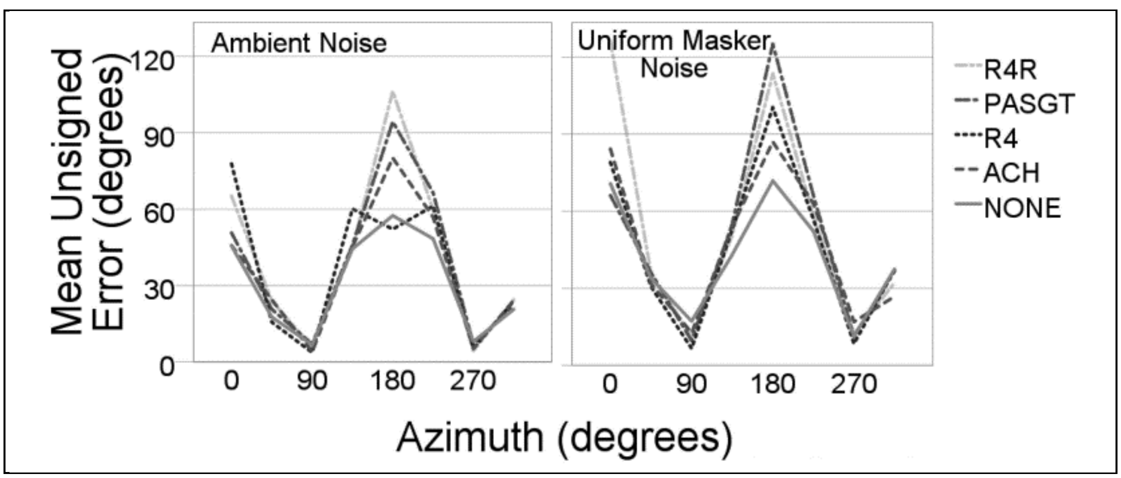

Figure 9. Unsigned error as a function of sound source azimuth for each of the two background noises.

With the exception of the R4R helmet, local unsigned error (computed after removing errors greater than 90° from the data) varied less than 3° as a function of the helmet worn. For the R4R, when localizing high-frequency stimuli, local error was 4.4°. These small differences support the thesis that most of the observed differences in overall localization performance are due to reversals.

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*Note that the error bars are 95% confidence intervals. A good rule of thumb is that there is a significant difference at ~ $p < 0.05$ between conditions if the overlap is less than a half of one one-sided error bar.

The direction-dependent spectral changes that serve as monaural cues result from reflections of the original sound source off the pinnae, head, and shoulders, and are dependent on the listener's physical profile. Thus, it is expected that profile changes due to helmet use will result in increased numbers of reversals that occur.

To assess the contribution of reversals, the percentage of errors larger than 90° was computed for the data from each of the helmets and this value was compared to the number of similar errors for the bare-head condition for each of the signal types (figure 10). The data displayed in figure 10 clearly show that wearing any helmet increases the probability of front-back errors. Recall that these values represent the *increase* in reversals, not the absolute values. Consequently, since the overall errors were already larger for the low-frequency stimuli, most likely because of the lack of high-frequency content, the observed increases are less. With the exception of the ACH, greater increases in reversals occurred for the high-frequency stimuli, consistent with the prediction that helmets affect the high-frequency spectral content considered to be important for monaural cues. The relatively small increase in reversals caused by the ACH for the high-frequency signals may be due to the absorption of reflected sounds by its padding. The effects on the low-frequency signals by both the PASGT and the ACH are likely due to shadowing effects of the Kevlar shell. Interestingly, there was no significant difference between the two R4 prototypes for the low-frequency stimuli, consistent with the observation that the changes in attenuation occur predominantly in the higher frequencies and these frequencies feature the cues needed to prevent reversals. Note that the number of reversals induced by the R4R prototype was less than that of the PASGT, but the total error was larger, suggesting that the majority of R4R errors were less than 90° and would be defined here as local errors.

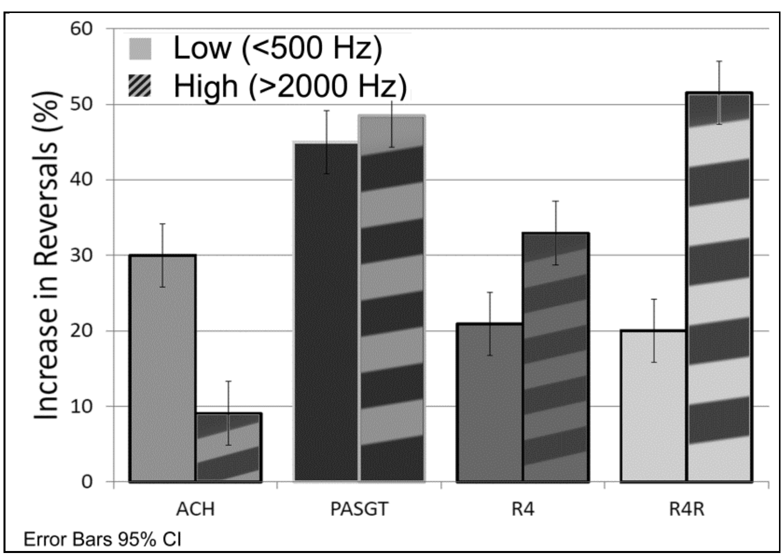

Figure 10. Reversals, defined as errors greater than 90°. Percent increase (relative to the bare-head condition) in the number of trials in which a reversal occurred for each of the signal types.

To compare and analyze the sources of localization errors caused by four helmets, an ANOVA was computed on the unsigned error data with the four independent variables as factors (five helmet conditions, times eight azimuth angles, times two stimuli, times two background conditions). Table 3 summarizes the main effects and the significant interactions ($\alpha < 0.01$*) revealed by the ANOVA.

Table 3. ANOVA results of analysis of localization error. For the interactions, the table shows significant effects only ($\alpha < 0.01$).

Source	***Df***	***F***	***Partial η^2***	***p***
Helmet	4	9.26	0.569	0.001
Error	*28*	*(553.2)*	—	—
Azimuth	7	8.80	0.557	0.001
Error	*49*	*(15,721.8)*	—	—
Background Noise	1	19.85	0.739	0.003
Error	*7*	*(1896.6)*	—	—
Spectral Content	1	.71	0.091	0.429
Error	*7*	*(1813.3)*	—	—
Helmet x Azimuth	28	2.39	0.091	0.001
Error	*196*	*(1108.1)*	—	—
Helmet x Spectral Content	4	4.17	0.373	0.009
Error	*28*	*(411.4)*	—	—
Masker x Spectral Content x Azimuth	7	3.81	0.352	0.002
Error	*49*	*(995.8)*	—	—

Note: Values enclosed in parentheses represent mean square errors.

As expected, there were effects of azimuth [$F(7,49) = 8.8$, $p < 0.001$] and background noise [$F(1,7) = 19.85$, $p = 0.003$] on the size of localization error. The pattern of errors shown in figure 9 reflects the fact that reversals cause large average errors at the front and rear angles. Errors are comparatively smaller at lateral angles. Localization performance was also poorer, as expected when there were higher levels of background noise and poorer signal to noise ratios (Abouchacra et al., 1998; Lorenzi et al., 1999). Significant differences between the effects of various helmets on the size of the localization error revealed by planned comparisons (contrasts) are shown in table 4.

Table 4. Significant results of a planned comparison of localization error as a function of the helmet worn.

Source	***Df***	***F***	***Partial η^2***	***p***
Bare vs. Helmets	1	15.25	0.685	0.006
Error	*7*	*(503.1)*	—	—
ACH-R4 vs. PASGT-R4R	1	10.41	0.598	0.015
Error	*7*	*(86.5)*	—	—

*Why $\alpha < 0.01$? From past experience with similar studies of localization performance with multiple experimental variables, we have found that using $\alpha < 0.05$ resulted in significant effects that, when examined, do not correspond to differences in performance that are of practical importance.

Wearing a helmet significantly increased localization error [$F(1,7) = 15.25$, $p = 0.006$]. There were no significant differences between the R4 and the ACH; both helmets provided similar head coverage (table 2). Performance with either the ACH and the R4 was significantly better than with the PASGT helmet or the R4R [$F(1, 7) = 10.41$, $p = 0.015$]. This is an especially important finding because the only difference between the R4 and the R4R is the addition of mounting rings that encircle the ears. These rings, as noted previously, slightly increase (3 dB) detectability of sounds with energy at 1-kHz range but are detrimental to sound source localization.

The ANOVA results listed in table 3 show a statistically significant interaction of helmet type with azimuth [$F(28,196) = 2.39$, $p < 0.001$] due to the fact that the main difference between helmets was the percentage of errors due to reversals. Listeners were more likely to perceive sounds as coming from the front when wearing the PASGT. The PASGT has a small ridge in the front that helps to direct sound energy from the front, but the lower profile impedes sound energy from the side and rear. In contrast, with the R4R listeners were more likely to misjudge sounds coming from the front as coming from the rear, perhaps because it was the only helmet with mounting rings that disrupted sound from the front. In fact, for three participants wearing the R4R helmet, it seemed as if they reversed nearly all items presented from 0° or 180°.

There was no main effect of spectral content (low-frequency energy vs. high-frequency energy); however, it interacted with the helmet type. This was a somewhat surprising finding since we expected that sounds with higher spectral content would be more localizable than those without content that could be used for monaural cues. However, figure 8 showed a mixed pattern of effects across the different helmets. It is possibile that the distortion of spectral information in higher frequencies by the R4R (e.g., greater attenuation of high-frequency energy by the helmet compared to attenuation of mid- and low-frequency energy) actually made those targets more difficult to localize, making a high-frequency content of no advantage. As figure 10 suggests, alteration of high-frequency spectral content by helmet wear made listeners vulnerable to front-back reversals that were already present in the localization data for low-frequency stimuli.

4. General Discussion

The primary objective driving the design of this experiment was to validate the use of a small portable array in less than ideal acoustical conditions for the ongoing evaluation of the effects of helmets on auditory detection and localization performance during the development of helmets. The experimental conditions in which the array was used represented typical enclosed-space conditions that could negatively affect the sensitivity and reliability of the collected data in comparison with the data that would be obtained under well-controlled laboratory conditions.

However, analysis of the collected data showed sufficient sensitivity and validity of the data to warrant the use of a small four-loudspeaker array to provide firsthand information about general acoustic effects of specific helmet forms. No significant biases that could be attributed to the rooms' acoustics have been identified for the proposed field array/test method. The magnitude of the errors obtained were large, especially for the diagonal angles, but these seem to be a function of the response method used; listeners gave numerical estimates of loudspeaker locations and were required to interpolate between values on a chart for the diagonal locations. Note that in another study of the effects of the ACH and the PASGT helmet on localization, average unsigned azimuth error values were approximately 41° and 48°, respectively. Performance with a bare head was approximately 35°. This test was done in a laboratory with controlled acoustical conditions and the response method was a rotating chair that was instrumented with a laser pointer and a compass (Scharine, et al., submitted). Further, although the sample size is relatively small, we typically require only 10 to 12 participants for studies of localization because the performance effects are measured with respect to their own baseline performance. The effects reported here are statistically significant using the more conservative criterion of $p < 0.01$.

A person's ability to localize sound is characterized by a head-related transfer function (HRTF), which refers to the physical changes to the sound wave as it travels from its source to the listener's ear (Moore, 2012). The binaural cues of level and phase differences are fairly robust; however, they can only help to determine locations on the left-right axis. The other type of localization cues are the monaural cues, which are the small spectral changes that occur as the sound wave is reflected from the surfaces of the head, ears, and torso. These reflections modify the original waveform, creating spectral peaks and notches through the addition of delayed sound reflected from helmet features. The observed insertion losses caused by individual helmets were not large—no more than ±10 dB at any frequency and average about 1.5 dB. However, the directionally dependent spectral shifts found for the HRTFs of the bare head are of a similar magnitude. Thus, while a helmet may have very small practical effects on sound detection, it does affect sound source localization. Because monaural cues are important for distinguishing the front from the rear hemisphere, this effect will most likely be observed for sounds originating from near 0º or 180°, where the error due to a front-back reversal is already largest.

Although all of the evaluated helmets affected the region around the ear by changing the spectral content of the signal reaching the ear, the changes to the spectral profile differed with helmet. Correspondingly, helmet effects on localization performance differed. The R4 prototype had relatively little attenuation and this attenuation was independent of frequency and angle of incidence. Thus, better localization performance might be predicted. Similarly, despite the increasing attenuation with increasing frequency measured for the ACH, this attenuation was independent of the direction, and thus localization performance was similar to that of the R4. As long as helmet attenuation is direction independent and is kept in reasonable range, it does not appear to affect the localization ability of the wearer. The most atypical pattern of attenuation and localization was observed for the R4R. This was due to the unusual amplification characteristic as a function of frequency and greater attenuation of sounds arriving from the front than from the back.

The detrimental effects of helmets on auditory localization ability reported here are consistent with other research conducted in our laboratory using a 12-loudspeaker array in an acoustically treated facility (e.g., Scharine, 2009). Although early localization research with helmets conducted by Randall (1971) and Randall and Holland (1972) showed only small differences between the bare head and helmet conditions, they reported reversals as correct responses. The data reported here did not differ significantly as a function of the helmet worn when reversals were removed from the data.

Consistent with the data reported here, Randall and Holland found smaller errors in the front than the rear. This pattern has also been found in more recent studies comparing localization accuracy with the ACH and the PASGT helmets in reference to that of a bare head. These show clear increases in localization error (with reversals trimmed) of approximately 5° to 9° in the rear hemisphere (Letowski, 2003).

When errors have been corrected for reversals or trimmed, the remaining error shows the reduction in spatial acuity or, rather, the blurring that occurs due to the helmet. An entirely different and graver picture emerges when the data are not corrected for reversals as shown by Scharine and her colleagues (Scharine et al., 2007), who compared the acoustic effects of helmets with varying levels of ear coverage in both semi-anechoic and normal reverberant conditions. If errors due to reversals were removed from the data, there was little difference between the helmets and the errors are small, i.e., less than 15° on average. If reversals are included, the largest errors occur near 0° and 180° because a reversal suggests a 180° shift in perception at those angles. Thus, larger errors generally indicate the occurrence of reversals. Scharine and her colleagues found that as ear coverage increased, the number of large errors (defined as greater than 25°) increased significantly. With no helmet, only 10.5% of the estimates were more than 25° off target. With a helmet that had no ear coverage, this number increased to 18.8%. A helmet with coverage similar to that of the ACH was 24%. Thus, nearly one-quarter of the trials resulted in estimates that were probably influenced by front-back confusions.

The importance of the findings reported here depends on the degree to which localization performance is essential to the Soldier’s safety and ability to complete his/her mission. Auditory information is often the first signal of events occurring in the Soldier’s environment. The observed differences in performance were mostly accounted for by increases in front-back reversals. Such errors are large. To some extent, head movement and visual cues will correct misperceived auditory information. However, increases in ambiguity can lead to increased uncertainty, stress, response times, and, consequently, errors.

It is important to consider the tradeoff between perceptual sensitivity and ballistic protection when designing personal protection equipment. A helmet may have slightly less ballistic head coverage but may greatly increase Soldier safety and mission effectiveness by preserving natural auditory situation awareness. One way to minimize changes is to leave the ears uncovered. The edges of the ACH and the R4 helmet are sufficiently far away from the ears to allow close-to-natural localization ability. However, simply ensuring that the ear is not covered is not sufficient. The only difference between the R4 helmet that allowed good performance and the R4R helmet that did not is a ring that circles but does not cover the ears.

The resulting loss of auditory information and compromised environmental auditory awareness can be just as lethal to the Soldier as the absence of ballistic protection for the head. Loss of early and proper identification of the threats and the directions they are coming from affects both Soldier safety and mission effectiveness. A good understanding of helmet effects is especially important in the urban environment, where directional information is very weak and confusing (Scharine and Letowski, 2005). The data obtained from the portable array successfully captured the helmets' direction-dependent effects on the spectral profile of sound events and provided an estimate of their relative effects on sound source localization. Thus, from a practical standpoint, it is a viable alternative to data collected in a more acoustically controlled setting.

5. Conclusions

A portable test facility consisting of a frame with four loudspeakers was used to measure the effects of four helmets on sound detection and localization for sounds coming from eight equally spaced azimuthal locations. The average helmet induced attenuation was less that 1.5 dB; however, these effects varied by azimuthal angle, frequency, and helmet type. These small changes to the spectral profile corresponded to significant differences in localization performance. For the most part, better localization performance was observed if the helmet-induced changes to the spectral profile were directionally independent, that is, not differing as a function of angle. Although the average localization errors reported in this study are somewhat larger than those reported by other authors (e.g., Oldfield and Parker, 1984; Butler, 1986), these data agreed with trends observed in our previous data obtained for the ACH and PASGT helmet in extensive laboratory studies. Therefore, the data obtained by a small loudspeaker array under less than optimal acoustic conditions can serve as a good guide for comparing general features of various helmets or trends resulting from helmet modifications, but are too crude to serve as the actual quantative data describing the specific helmets.

In summary, the results of the described study support the notion that a small portable four-loudspeaker test array allows one to evaluate the general acoustic properties of various helmet designs and their effects on auditory perception of helmet wearers. As the data presented here suggest, the greater detriment to a helmet wearer's auditory awareness is not the reduced sensitivity to the presence of sound events but rather the distortion of the cues used to locate those events in space. The attenuation measurements for each helmet differ with signal frequency and angle of incidence, and these differences depend on the helmet worn (e.g., PASGT helmet vs. ACH and R4R vs. R4). However, it can be shown that even these small shifts may affect localization of sound sources by changing the relative spectral content of the perceived sound. In these respects, the data obtained with the inexpensive portable four-loudspeaker array in real-world enclosed acoustical conditions may serve as a valuable firsthand account of helmet properties and the presence or lack of presence of desired effects caused by helmet modifications.

6. Key Points

- A helmet's form factor can greatly affect auditory localization ability of the wearer.
- Helmets can decrease or increase detectability of sound sources, but these effects are very small except for high frequencies.
- Any element of a helmet that is close to the ear degrades the user's auditory performance.
- A simple four-unit loudspeaker array is sufficient for use in quality control and field wear, but more precise equipment should be used to establish standards definitions and type classification.

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